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COMPARISON OF SPECIFIC ABSORPTION RATES INDUCED IN A MODEL OF THE HUMAN SKULL

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În acest articol, valorile ratelor specifice de absorbție induse în interiorul unui model al craniului uman, corect anatomic, au fost evaluate şi comparate. În scenariile de expunere la radiații electromagnetice studiat, doi parametri au fost variația, frecvența şi poziția sursei, iar pentru obținerea rezultatelor a fost folosit un program numeric bazat pe metoda diferențelor finite în domeniul timp. Au fost trase concluzii şi subliniate direcții de cercetare viitoare.

In this article, the specific absorption rates induced inside an anatomically correct human skull were calculated and compared for several electromagnetic radiation scenarios. Five positions and four frequencies were considered for the source and a finite difference time domain method based software was used in obtaining the results. Conclusions were drawn and directions for future work outlined.

Keywords: anatomical model, finite difference time domain method, specific absorption rates

1. Introduction

Nowadays, it is common place to find systems based on radiofrequency and microwave technologies at home, in workspaces, hospitals, schools and virtually everywhere, both outdoors and indoors. This development is seemingly unstoppable, yet at the same time, public fear about possible adverse effects to human health from electromagnetic radiation has also been growing. It is well known that exposure to high frequency fields produces biological effects. Whether these effects are good or bad is yet to be determined with any kind of certainty, especially in light of the fact that relevant epidemiological studies conducted so far face a major disadvantage: mobile phones haven't been used long enough so as to permit the assessment of any modifications in the functioning of the human body or the development of any types of tumors [1].

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Two different exposure scenarios can be distinguished for mobile communications systems: that of the human head, due to the near field microwave emissions from handsets, and that of the general public due to base station antennas. Because of its popularity the mobile phone has received much more scientific attention than other sources of radiofrequency radiation, due to the fact that it is very close to the user's head, thus causing a complex exposure scenario difficult to measure.

2. Overview

When dealing with the human health issues in the near field between 100 kHz and 10 GHz, it is usual to provide basic restrictions on the specific absorption rate (SAR) values. SAR is the parameter employed to properly quantify the response of the biological structure in terms of the incident and induced field, of the energy absorbed and maintained inside the human body. It is the time derivative (rate) of the incremental energy (*dW*) absorbed by or dissipated in an incremental mass (*dm*) contained in a volume element (*dV*) of a given density (ρ), as seen in (1) [4].

$$SAR = \frac{d}{dt}\left(\frac{dW}{dm}\right) = \frac{d}{dt}\left(\frac{dW}{\rho dm}\right) \tag{1}$$

The SAR is expressed in units of watts per kilogram (W/kg) or equivalently milliwatts per gram (mW/g). It can also be related to the induced electrical field, through (2)

$$SAR = \frac{\sigma E^2}{\rho} \tag{2}$$

where σ represents the electrical conductivity of the tissue (S/m), ρ the density of the same tissue (kg/m3) and E is the intensity of the induced electric field (V/m).

The radiofrequency energy absorption phenomenon in the human body is a very complex issue. Tissue conductivity depends on frequency, constitution and temperature. The volumetric density, also changes with tissue type since it is a water content dependable variable. The electric field inside the body depends upon many other factors, such as the dielectric properties, shape, size, orientation, polarization and frequency, source configuration and exposure environment [1]. Thus, evaluating the specific absorption rates distributions associated with handheld devices is a complex task, usually accomplished by numerical modeling or appropriate and specific measurement techniques.

One of the most commonly used numerical models is based on the finite-difference time-domain (FDTD) method which represents a numerical algorithm for solving Maxwell's differential equations of the electromagnetic field interactions, described by (3), in the time domain [2]. This is accomplished by dividing the space into unit cells in which the spatial and temporal derivatives of the electric and magnetic fields are directly approximated by simple, second-order, accurate, central-difference equations.

$$\begin{cases} \nabla \times \mathbf{E} = -\mu \dfrac{\partial \mathbf{H}}{\partial t} \\ \nabla \times \mathbf{H} = \sigma \mathbf{E} + \varepsilon \dfrac{\partial \mathbf{E}}{\partial t} \end{cases} \tag{3}$$

where **E** is the electric field vector, **H** the magnetic field vector, μ the magnetic permeability and ε the dielectric permittivity.

Among other, the FDTD uses the concept of time origin, which means that the source of the electromagnetic energy is turned on at a specific moment in time. Up to that moment, it is considered that there was no other source, electromagnetic or otherwise [2].

$$\begin{aligned} & H_x(x, y+\Delta y/2, z+\Delta z/2; t+\Delta t/2) = \\ & = H_x(x, y+\Delta y/2, z+\Delta z/2; t-\Delta t/2) + \\ & + \frac{\Delta t}{\mu \Delta z}\left[E_y(x, y+\Delta y/2, z+\Delta z/2; t) - E_y(x, y+\Delta y/2, z; t)\right] + \\ & + \frac{\Delta t}{\mu \Delta y}\left[E_z(x, y, z+\Delta z/2; t) - E_z(x, y+\Delta y/2, z+\Delta z/2; t)\right] \end{aligned} \tag{4}$$

Starting from the origin of time, the propagation and scattering of the fields are obtained by solving the equations depicted by (3). For example, if Δx, Δy, Δz and Δt represent the space and time increments, and the position of the vector components of the electric and magnetic fields are situated according to the grid in fig. 1 [2], then the difference equation for one scalar equation [2], can be written as in (4). For the other components of the electromagnetic field, namely E_x, E_y, E_z, H_y, H_z five more similar equations with (4) can be determined.

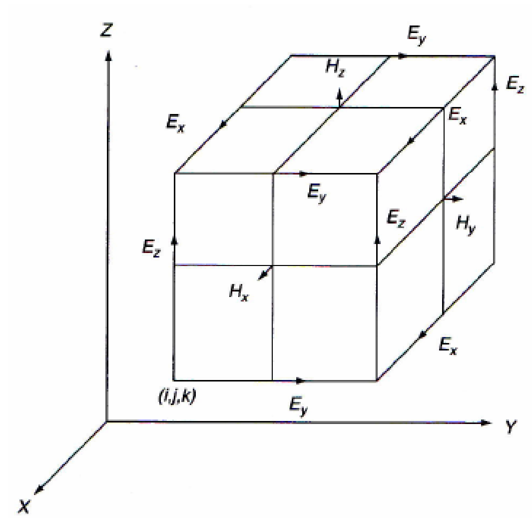

Fig. 1. Example of a Yee cell for which the position of the vector components of the electric and magnetic fields can be observed

3. Numerical Model

The central nervous system, which controls the entire human body and its interactions with the surrounding environment, is largely located in the brain, inside the head. The use of a mobile phone implies positioning it next to the ear, thus placing the radiation antenna close to the brain. Because of this, many studies regarding the effects of electromagnetic radiation on human health have focused on the head. From this point of view, it is important to determine whether the skin, bones and meninges play any role in reducing the electromagnetic field induced inside the human head that actually reaches the surface of the brain, and if they do, to what extent.

The results presented below were obtained from simulations run in a numerical program that uses the finite difference time domain method in solving Maxwell's field equations.

In order to properly determine the induced electromagnetic field and through it the specific absorption rates, several steps had to be taken into account. First, an anatomically correct model of the geometry of the human skull was created by the authors with the help of a graphic modeling software. The skull is a highly complex structure consisting of 22 bones altogether. These can be divided into two sets, the cranial bones and the facial bones. While the latter form the framework of the face, the cranial bones form the cranial cavity that encloses and protects the brain. Most skull bones are flat and consist of two parallel compact bone surfaces, with a layer of spongy bone sandwiched between. The spongy bone layer of flat bones predominantly contains red bone marrow and hence has a high concentration of blood. The model was created outside the simulation program, as a CAD (Computer Aided Design) file and then imported into the software. The dimensions were taken from [3] and the geometry obtained is described in fig. 2.

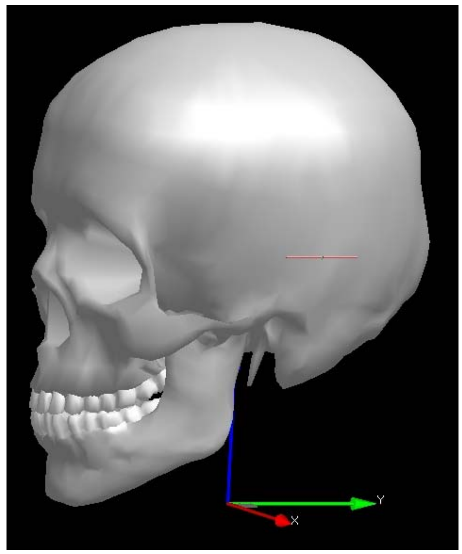

Fig. 2. Anatomical model of the human skull

Along with the model of the skull, fig. 2 also depicts the placing of the source of the electromagnetic radiation. International standards [4] have concluded that for a better interpretation and comparison of the results from different researchers and in order to avoid any uncertainties that might appear, a default geometry for the source should be used. Because of its simplicity and high degree of repeatability, a dipole was chosen. In Fig. 2, the antenna can be seen placed parallel to the skull, on its left side. In reality, the skull in covered by skin and hair, and generally the phone is next to the ear, so, during simulations, a distance had to be introduced between the dipole and the bones. This distance is measured along the x axis of the reference system, also visible from Fig. 2. The minimum for this distance was 1,5 cm from the margin of the skull model. Any anatomically correct geometry has to be completed with proper dielectric properties for all the associated materials. They were established from [5] for both bones and teeth.

Another step in quantifying the induced field, essential in any numerical calculations, is the creation of the mesh. This means that the volume of interest has to be divided in cells. When choosing the dimensions of the cells, one has to remember that reducing the dimensions of the cells has a direct impact on the errors that result when applying the finite difference time domain method. However, these dimensions have a negative impact on the memory requirements of a computer that runs a particular simulation. Basically, small dimensions lead to a big number of cells and more memory. Also, the geometry of the skull is irregular with round and concave surfaces that cannot be properly represented with cubes, unless they are small. The results of the mesh must not modify the geometry of the model. So, a balance has to be achieved between memory, shape representation and errors in calculations. For this particular model of the human skull, a grid of 1 mm x 1 mm x 1 mm was used in the end which resulted in the need of approximately 1GB of memory for each radiation scenario that was simulated.

4. Simulation Results

Numerical simulations were run for four frequencies, namely 2,5 GHz, 3,5 GHz, 5,4 GHz, 5,8 GHz and five different positions of the dipole antenna relative to the head skull, named “1,5”, “6,5”, “11,5”, “5(sus)” and “10(sus)”. The values for the frequencies were chosen to be equal or close to those employed in the WiMAX communication system. The difference between positions is given by the placing of the electromagnetic source. For the first three, the dipole moves further and further away from the model, across the x axis, but, at the same time, maintaining its coordinates along the other two axes. Basically, it stays parallel with the position presented in Fig. 2, but increases the distance from the skull by adding first 5 cm, for “6,5” and then 10 cm for “11,5” to the original “1,5” position. For the last two imagined situations, “5(sus)” and “10(sus)”, the antenna moves up relative to the model, along the z axis, while keeping the values for the other coordinates constant.

The dipole was made up by two cylinders, whose diameter was chosen such that the approximation of a thin dipole could be assumed. The applied excitation was a voltage source with a sinusoidal input. All calculations were run for the same number of time steps. Following the simulation, the input power was adjusted from the computed value to the specified 1 W [4].

The results for each simulation scenario are presented in Tables 1 and 2. However, for a better understanding and interpretation of the results, graphical representations were preferred. Because during calculations, two parameters were varied, first the frequency and then the distance between the model and the electromagnetic source, the graphs can the divided into two categories. The first, comprising of fig. 3 and fig. 4, compares the results from the point of view of the position of the antenna, while the second category, consisting of fig. 5 and fig. 6, uses the frequency of the source as criteria for comparison.

Table 1

Maximum specific absorption rates averaged over 1g of tissue

Antenna Position (cm)	MAX SAR 1g			
	2,5 GHz	3,5 GHz	5,4 GHz	5,8 GHz
1,5	6,8160E+00	7,7520E+00	8,9069E+00	9,0652E+00
6,5	5,8386E-01	9,6659E-01	1,5876E+00	1,7207E+00
11,5	2,8043E-01	4,9385E-01	8,2127E-01	8,9757E-01
5(sus)	5,7652E+00	5,9950E+00	6,7977E+00	7,1024E+00
10(sus)	7,9119E-01	1,2058E+00	1,5561E+00	1,6559E+00

Table 2

Maximum specific absorption rates averaged over 10g of tissue

Antenna Position (cm)	MAX SAR 10g			
	2,5 GHz	3,5 GHz	5,4 GHz	5,8 GHz
1,5	4,5655E+00	4,6798E+00	4,5229E+00	4,4842E+00
6,5	3,4719E-01	4,1714E-01	6,0902E-01	6,2236E-01
11,5	1,4993E-01	2,0932E-01	2,7707E-01	2,7022E-01
5(sus)	4,1727E+00	4,0433E+00	3,8999E+00	3,9602E+00
10(sus)	6,4135E-01	9,0601E-01	9,9199E-01	1,0271E+00

As seen in fig. 3 and fig. 4, the values for the specific absorption rates, either the ones averaged over 1 gram of tissue or those over 10 grams, decrease when the distance between the dipole and the skull increases. The further the mobile phone is held relative to the human head, the smaller the intensity of the induced electromagnetic field and through it, the SARs. Out of the five positions studied, in the "11,5", for which the distance is 11,5 cm from the margin of the skull geometry, the smallest values were obtained. The descent slope for the scenarios when the dipole moves up relative to the skull in slower than the situation in which the source moves further away (comparing positions "1,5", "5(sus)" and "10(sus)" with "1,5", "6,5" and "11,5"). This is explained by the fact that the electromagnetic field emitted by the dipole travels through the air before reaching the model of the skull and in open space, the intensity of the field decreases with the square of the distance between the point of origin and the point of evaluation. For "6,5" and "11,5" there are first 5 cm and then 10 cm between the above mentioned points, while for "5(sus)" and "10(sus)" the coordinate of the dipole across the x axis is constant, so the intensity that reaches the model is the same.

However, the induced field and the specific absorption rates depend not only on the amplitude of the emitted one, but also on the surface on which the radiation takes place.

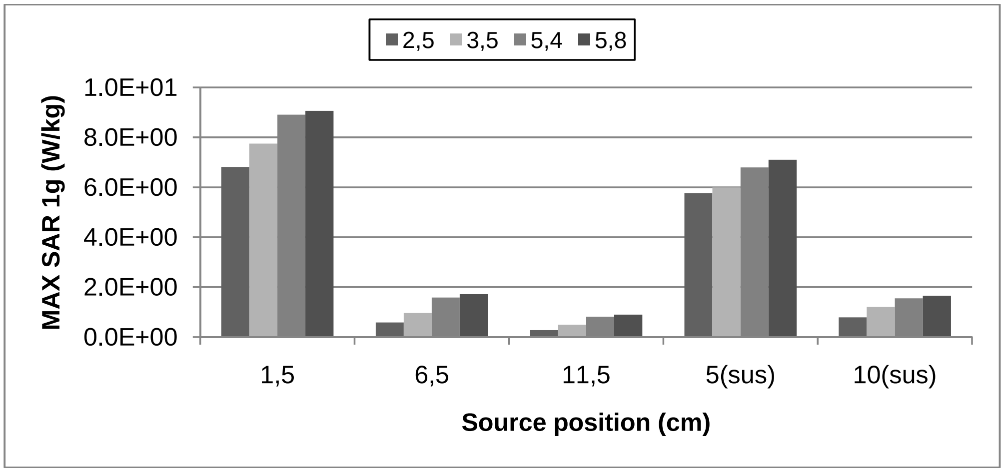

Fig. 3. Maximum simulated SAR averaged over 1g of tissue grouped according to source position

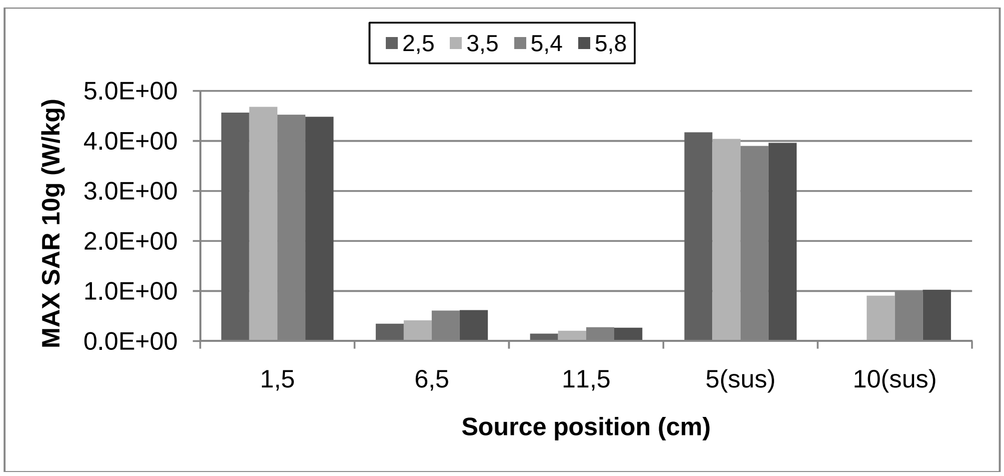

Fig. 4. Maximum simulated SAR averaged over 10g of tissue grouped according to source position

The dipole radiates electromagnetic energy in a toroidal radiation pattern where the axis of the toroid centers about the dipole. Depending on the relative position of the skull to the antenna, the area obtained when intersecting the model with the radiation pattern, namely the irradiated surface, will have different sizes. For "10(sus)", compared to "1,5" and "5(sus)", this area is the smallest, thus justifying the reduction in value for the specific absorption rates. The diverse slope also points out the different proportions in which field amplitude and radiation surface influence the electromagnetic field induced inside any part of the human body.

Concerning the second type of graphical representations, made up of fig. 5 and fig. 6, there are no major differences for the values of the specific absorption rates, evaluated for several frequencies of the electromagnetic source. In the case of the SARs mediated over 1 gram of tissue, a slightly increase with frequency can be observed, while for those averaged over 10 grams this effect is further reduced.

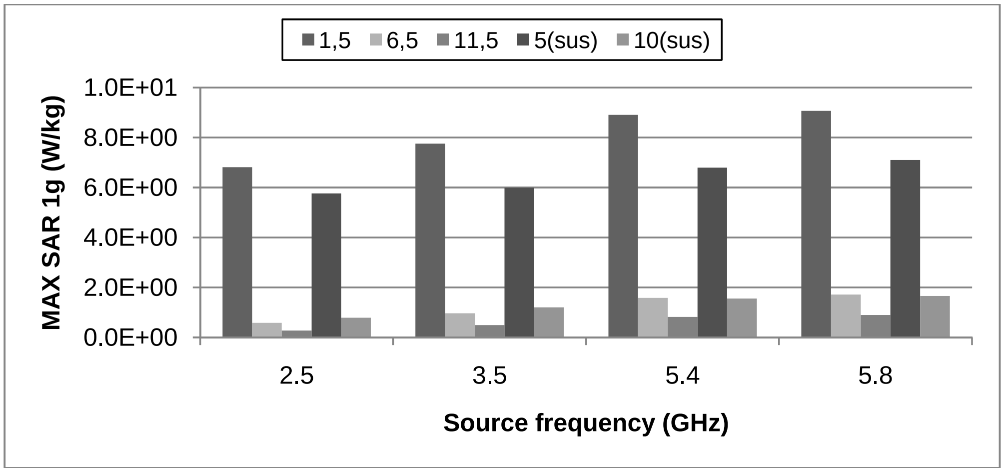

Fig. 5. Maximum simulated SAR averaged over 1g of tissue grouped according to source frequency

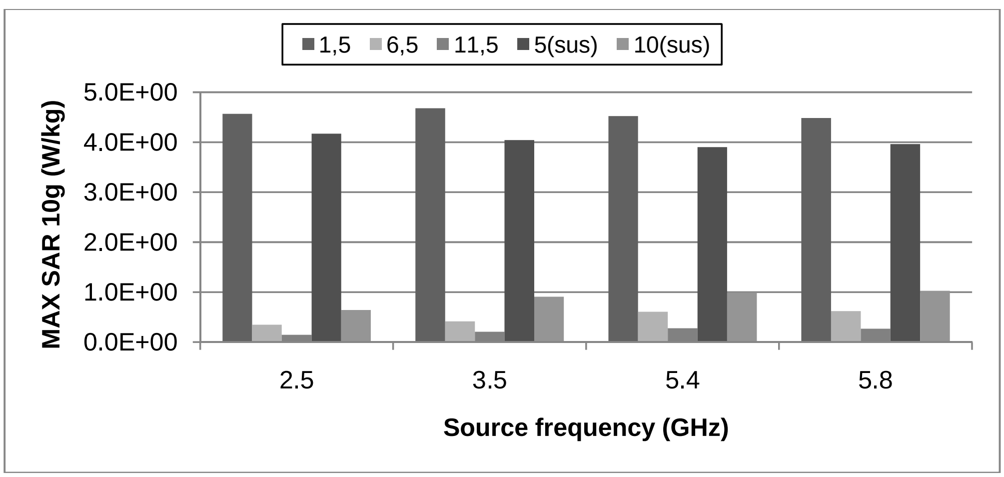

Fig. 6. Maximum simulated SAR averaged over 10g of tissue grouped according to source frequency

From the results presented in Tables 1 and 2 for the specific absorption rates, a general aspect should be underlined: the values for the SARs evaluated over 10 grams of tissue are not ten times smaller than those averages over 1 gram. Human tissues in general, and the bones of the human skull make no exception, are anisotropic mediums, and although the definitions for both types of specific rates are the same, the phenomena of the electromagnetic field induction and interaction are different and should be treated accordingly.

5. Conclusions

This article has presented a comparison between different radiation scenarios. A model of a heterogeneous skull model has been created by the authors and then tested by exposing it to the electromagnetic field emitted by a dipole. The results have shown that the total radiated power, the placing and the frequency of the source play a major part in accurately determining the values of the induced field and of the specific absorption rates. Also, a general response for any and all frequencies cannot be predicted and extrapolations from previous results may prove incorrect.

The geometry proposed is highly versatile. It may be used for future research, involving several electromagnetic sources, modulated fields or it may be adapted to the specific characteristics of certain individuals for particular case studies.

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